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16. Abstract
This study, using black fuel-fire generated smoke, is a partial replication of an earlier study using an inert white smoke as the obscuring agent in the study of the readability of smoke-obscured, self-illuminated emergency exit signs.

The results indicate that, within the range of sign sizes and background luminance levels studied, and under otherwise favorable viewing conditions, most of the signs were read through black smoke with optical densities ranging between 3.0 and 4.0. At two standard deviations below the means, most of the size and luminance level combinations were identified at optical densities ranging from approximately 2.5 to 3.0.

A comparison of the results with those obtained in the earlier study using white smoke, shows both colors of smoke to be approximately equal in their ability to shroud the illuminated signs. Black smoke, however, appears somewhat more effective in obscuring small details at or near the normal visual acuity threshold.

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READABILITY OF SELF-ILLUMINATED SIGNS
OBSCURED BY BLACK FUEL-FIRE SMOKE

Introduction.

Minimal design requirements for emergency exit signs used in civil air transports are specified in Federal Aviation Regulations (FAR) 25.812. These requirements insure adequate visibility and readability under normal viewing conditions. However, some emergency conditions, such as postcrash fires, may introduce smoke into the cabin area and obscure the signs at a time when their prominent visibility is most critical.

The present study, using black fuel-fire smoke, is a partial replication of an earlier study (7) that used an inert white smoke to investigate the readability of smoke-obscured, self-illuminated emergency exit signs of various sizes and background luminance levels. The use of an inert white smoke offers many practical advantages as a research tool, but a quantitative comparison with black smoke is required to determine its effective relative visual screening ability before it can be equated with, or used to predict visual performance in the presence of, black fire-generated smoke.

Methods.

Subjects. Subjects consisted of 11 male and 8 female adult volunteers and paid participants. Six subjects required corrective lenses to achieve 20/20 distant visual acuity. Ages ranged from 20 to 55 years with a mean of 35 years.

Equipment. The equipment arrangement is schematically illustrated in Figure 1 and is described in greater detail in the report on the study using white smoke (7).

The National Bureau of Standards (NBS) Photometric Smoke Measurement System was mounted beneath the subjects' line of sight and was physically obscured from view. The system was modified and calibrated for operation with a 50-cm (19.7-in) separation between the reference source light and the phototube detector.

A firebox was constructed from steel drums in which cotton rags soaked in JP-4 jet fuel and hydraulic oil were burned to generate the black smoke. The smoke was drawn through a screen to filter out the larger soot particles and collected in a cooling vessel, also constructed of steel drums. From there it was ducted to the smoke chamber as needed and evenly dispersed by a small agitating fan mounted in a corner of the chamber.

Displays. The signs were composed of the characters "E, X, I, T" except that the largest sign was limited to two characters. Character sequences were varied to minimize anticipatory identification. The

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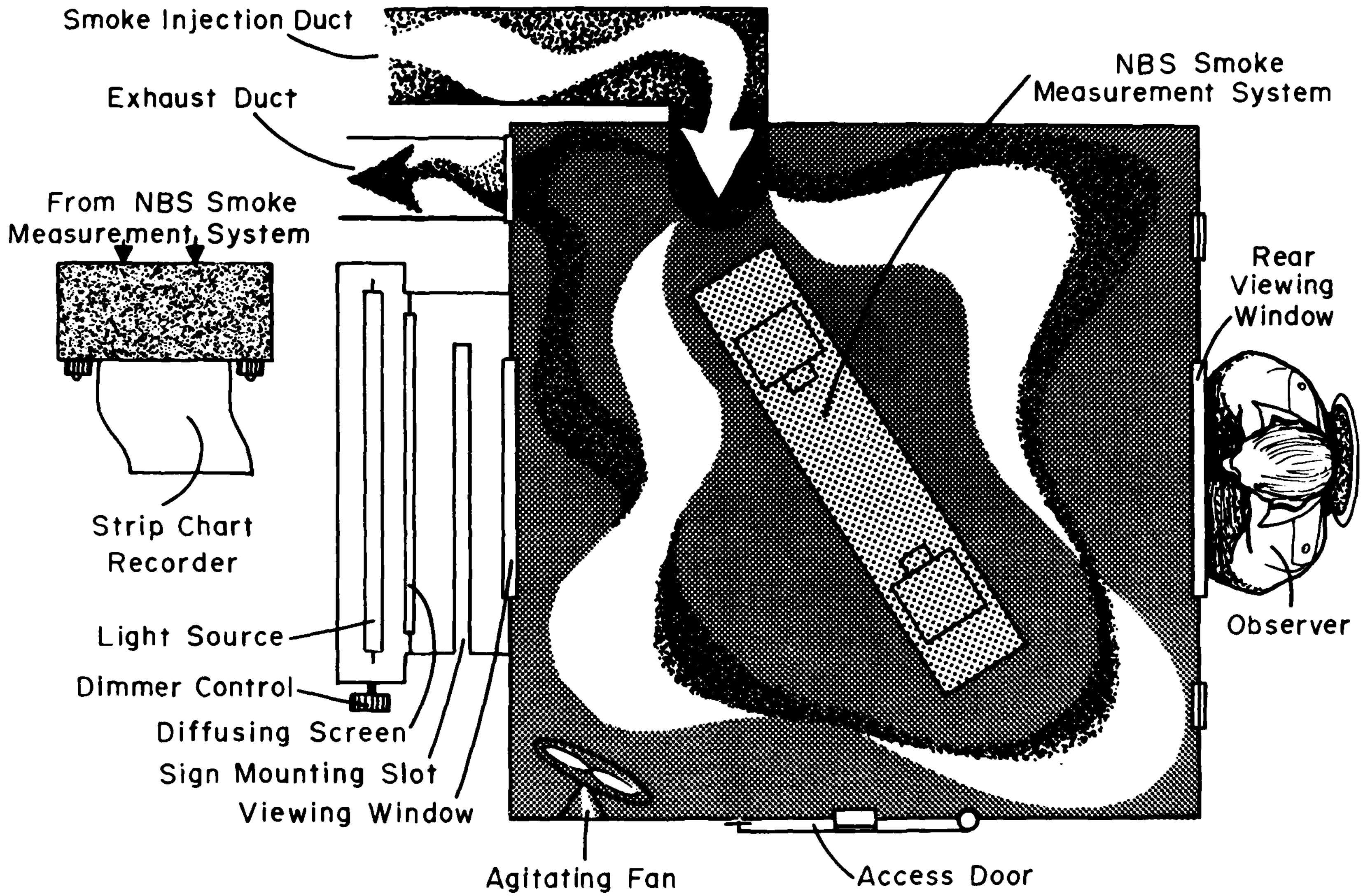

Figure 1. Diagram of experimental equipment configuration in the smoke chamber viewed from above.

character format was based on that used by the Grimes* exit light sign and is described in the earlier report. Table 1 gives the height and stroke width of the characters together with the corresponding visual angles for the 196-cm (77-in) viewing distance. The smoke chamber occupied 183 cm (72 in) of the total viewing distance. Sign No. 4 approximates the size commonly found on commercial aircraft.

TABLE 1. Character Sizes and Visual Angles of Experimental Signs

Sign No.	Character Height (mm)	(in)	Visual Angle (min)	Stroke Width (mm)	(in)	Visual Angle (min)
1	211.5	(8.33)	371.4	25.40	(1.00)	44.6
2	108.2	(4.26)	190.1	13.10	(0.52)	23.0
3	52.7	(2.07)	92.6	6.35	(0.25)	11.2
4	46.2	(1.84)	81.2	5.45	(0.21)	9.6
5	26.3	(1.04)	46.2	3.20	(0.13)	5.6
6	13.4	(0.53)	23.6	1.60	(0.06)	2.8
7	6.4	(0.25)	11.2	0.77	(0.03)	1.4

The three luminance levels were the average of measurements taken at 24 equally spaced grid points on the observer's side of the available viewing area of the diffusing screen before a sign was mounted for viewing. The 89-cd/m^2 (26-fL) luminance level is approximately the exit sign background luminance level required by FAR 25.812. The 31- and 158-cd/m^2 (9- and 46-fL) values were the minimum and maximum levels obtainable with the lighting system. The candela (cd) is the International System of Units (SI) unit of luminous intensity. The metric unit 1 cd/m^2 is approximately equivalent to 0.29 fL.

Procedure.

Prior to each test session the lenses and interior window surfaces were cleaned, the chamber sealed, the recording system zeroed to baseline, the largest sign inserted in the mounting slot, the luminance adjusted to the desired level, and the smoke introduced into the chamber until it reached a density at which the recording system no longer registered a measurable light output.

The subject, who had spent several minutes adapting to the mesopic ambient lighting condition, was then seated behind the rear viewing window with eye height adjusted to give normal line-of-sight viewing of the signs through the smoke-filled chamber. Smoke was then drawn out of the chamber by an exhaust fan at a controlled rate until it reached the density at which the subject could first distinguish the light from the sign. From this point the remaining smoke was allowed to dissipate at its slower normal rate until the subject correctly identified the sign. When a sign had been identified the next smaller sign was immediately presented until all seven signs had been identified.

*Grimes Mfg. Co., Urbana, Ohio, Emergency Exit Light 10-0067-9.

The output of the photometric smoke measurement system was recorded on a strip chart recorder. As the output rose from zero in dense smoke toward the clear air value, the chart was indexed at the values at which the subjects responded to each size of sign. The millivolt (mv) values recorded from the measurement system were converted to optical density values by the formula:

$$\text{Optical Density} = 1/d \log Tc/Ts$$

where: d is the unit distance between the reference light and the phototube (0.5m),

Tc is the clear air (mv) value,

and

Ts is the (mv) value at which the signs were identified.

Residual smoke deposits on the interior surfaces of the viewing windows resulted in an apparent increase in the effective smoke density as viewed by the subjects over and above the density measured by the system. These deposits, with a mean combined density of 0.17, and all falling within a narrow range of values, were found to accumulate during the time the chamber was being charged with, and during the initial evacuation of, the smoke prior to identification of the first sign. In the absence of significant increases of such deposits during the period of subject responses, a constant correction factor of 0.17 was added to the individual density values calculated from the output of the smoke measurement system.

Results.

The means, standard deviations, and ranges of the optical densities of black smoke at which the subjects could read the seven sizes of signs at three background luminance levels are listed in Table 2. Figure 2 plots the means for the total density values.

Increasing character sizes and background luminance levels made the signs readable at higher overall density levels, but the gains were relatively small in comparison to the magnitude of increases in physical size and luminance levels.

Figure 3 shows the density values two standard deviations below the means for the three background luminance levels. These are the values at which approximately 98 percent of the general population with 20/20 distant visual acuity and comparable brightness and contrast discrimination thresholds can be expected to be able to read similar signs under similar conditions. The ranges of density values spanned

TABLE 2. Means, Standard Deviations, and Ranges of the Optical Densities of Black Smoke at Which Signs With Seven Character Sizes Were Identified When Presented at Three Background Luminance Levels

Sign	Smoke Density (total)			Smoke Density (per meter)		
No.	Mean	S.D.	Range	Mean	S.D.	Range
31 cd/m^2 (9 fL)						
1	3.88	0.45	3.25 - 4.76	2.20	0.25	1.85 - 2.68
2	3.74	0.46	3.08 - 4.60	2.12	0.25	1.76 - 2.59
3	3.58	0.43	2.96 - 4.40	2.04	0.24	1.70 - 2.48
4	3.50	0.41	2.87 - 4.28	1.99	0.22	1.65 - 2.41
5	3.37	0.39	2.78 - 3.98	1.92	0.21	1.59 - 2.25
6	3.10	0.30	2.49 - 3.49	1.77	0.16	1.44 - 1.99
7	2.55	0.25	2.11 - 3.07	1.47	0.13	1.23 - 1.82
89 cd/m^2 (26 fL)						
1	4.05	0.47	2.98 - 5.08	2.29	0.25	1.71 - 2.85
2	3.91	0.42	2.92 - 4.73	2.21	0.23	1.67 - 2.66
3	3.75	0.43	2.83 - 4.73	2.13	0.23	1.62 - 2.66
4	3.63	0.38	2.82 - 4.17	2.06	0.21	1.62 - 2.36
5	3.48	0.38	2.75 - 4.03	1.98	0.21	1.58 - 2.28
6	3.20	0.38	2.56 - 3.80	1.83	0.21	1.48 - 2.16
7	2.71	0.33	2.33 - 3.56	1.55	0.18	1.35 - 2.02
158 cd/m^2 (46 fL)						
1	4.00	0.46	3.01 - 4.71	2.26	0.25	1.72 - 2.65
2	3.88	0.48	2.95 - 4.80	2.20	0.26	1.69 - 2.70
3	3.75	0.49	2.87 - 4.77	2.13	0.26	1.65 - 2.68
4	3.67	0.47	2.83 - 4.59	2.08	0.26	1.62 - 2.59
5	3.55	0.45	2.70 - 4.36	2.02	0.25	1.55 - 2.46
6	3.32	0.38	2.56 - 3.80	1.89	0.21	1.47 - 2.22
7	2.84	0.26	2.20 - 3.30	1.63	0.14	1.28 - 1.88

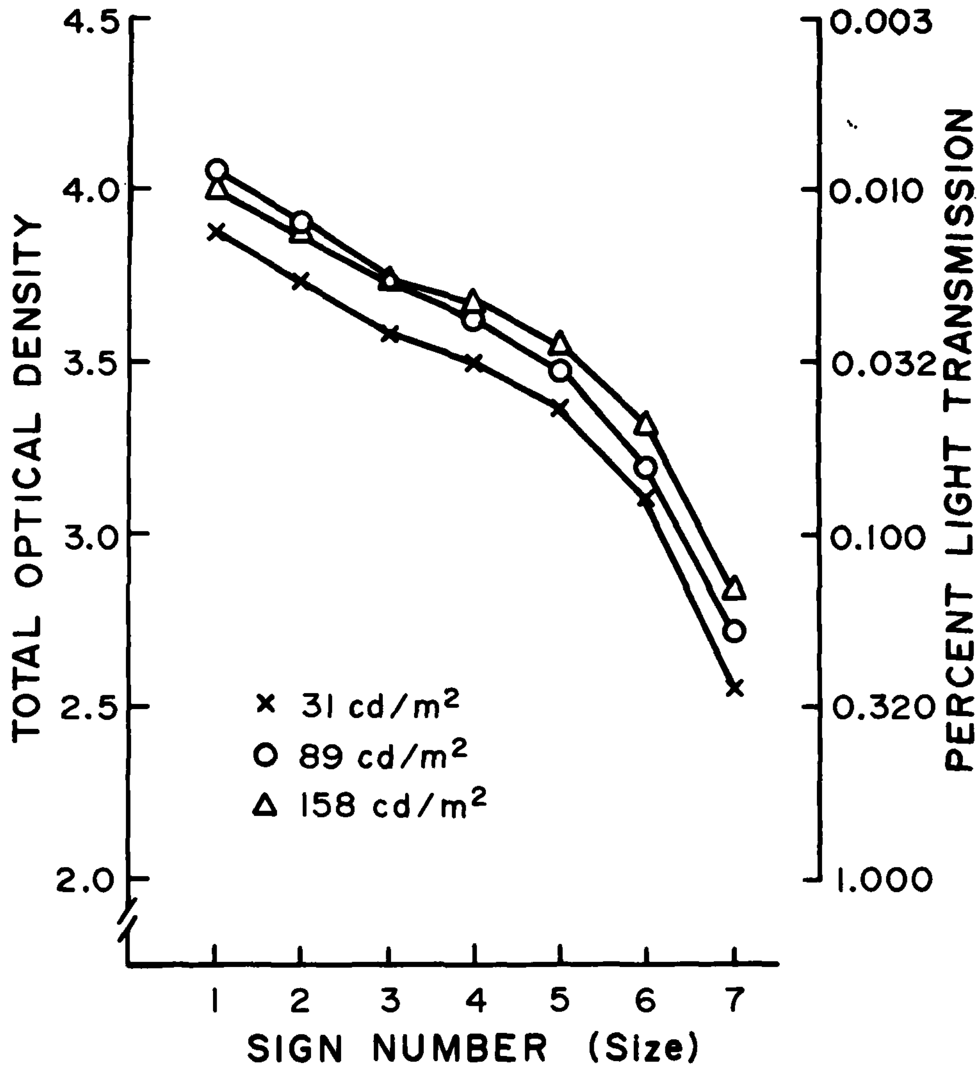

Figure 2. Means of smoke density values at which seven sign sizes were identified when presented at three background luminance levels.

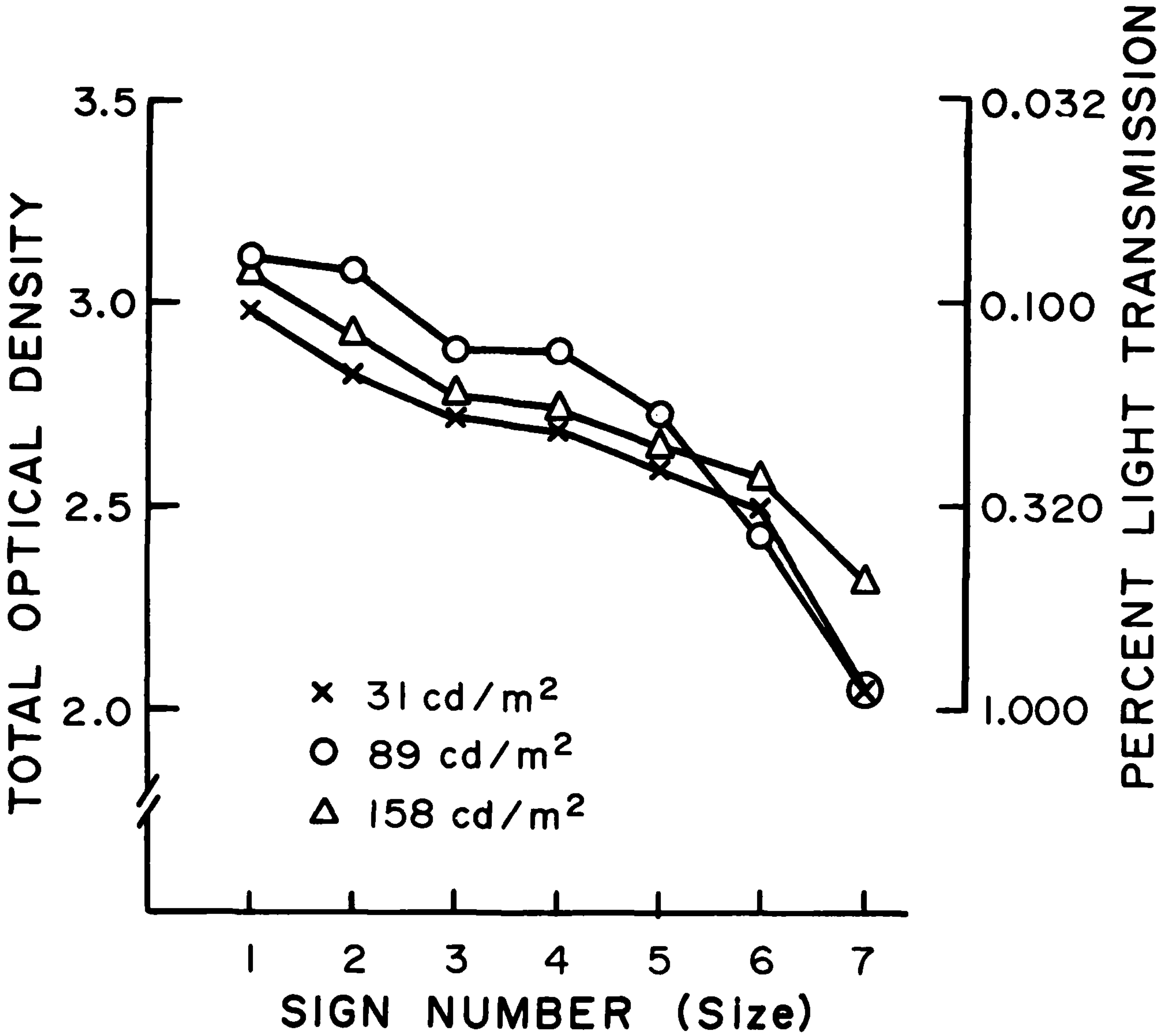

Figure 3. Density values two standard deviations below the means at which seven sign sizes were identified when presented at three background luminance levels.

by these data effectively reduce the apparent brightness of the signs to between 0.08 and 1.00 percent of the clear air values. Increasing character sizes still compensates in part for increasing smoke density, but the role of background luminance becomes less specific.

Discussion.

The density values reported in Table 2 are based on threshold determinations of what is just recognizably visible and do not evaluate the overall effectiveness of the signs in meeting their intended purposes in the presence of smoke. The subjects' knowledge of the location and nature of the signs, directed attention to the task, lack of situational distractions, and absence of any direct contact of the eyes with the smoke contributed to better visual performance than can be expected for aircraft passengers and crew under conditions involving smoke in the cabin area. For these reasons the reported density values should be considered the upper limits at which the signs can be read rather than the values at which comparable signs can be effectively read under actual emergency conditions.

Many factors contribute to establishing the brightness and contrast discrimination thresholds that determine visibility or legibility (1). At dim brightness levels, contrast ratios become more critical than at higher brightness levels (10,11). If a reaction time criterion is added to that of simple recognition, the advantage of higher contrast ratios and higher brightness levels becomes even more apparent (6,11). These thresholds are also related to age (8). A number of investigators have demonstrated a need by older age groups for more light and higher contrast ratios to make effective discriminations than is required by younger groups (4,6,10).

Common design practices for improving legibility and attention values of displays include increasing character size, increasing the luminance level, and increasing the contrast ratio between the legend and the background. The character sizes used in this study spanned, and considerably exceeded, the range of sizes listed by Smith (9) in his summary of recommended letter sizes used in various display applications with unobstructed viewing. The largest character height exceeded the high end of the recommended design range for critical data with fixed position and a luminance level below 3.4 cd/m^2 (approximately 1.0 fL) by more than 10 to 1 and the low end of the design range by more than 19 to 1. Sign No. 4, which approximates the size and format of the exit sign commonly found in the cabin area of commercial aircraft, exceeded these design recommendations by factors of 2.2 to 1 and 4.3 to 1, respectively. The character sizes in Signs Nos. 1 and 4, for example, have a height ratio of 4.6 to 1, but the increased densities at which the larger sign was identified were only doubled; i.e., the required light transmission was only halved. Increasing character sizes would therefore seem to be an inefficient method for overcoming increasing smoke densities.

Within the range studied, there is a marginal overall increase in the mean smoke densities at which the signs can be read as a function of increasing background luminance levels. However, increases past 89 cd/m^2 (26 fL) appear to be effective only for the signs with the smallest character sizes. The values two standard deviations below the means show the 89-cd/m^2 (26-fL) luminance level to be most effective for all but the two smallest character sizes. This change from the relative mean values results from variability of the standard deviations of the means at the 89-cd/m^2 (26-fL) luminance level.

With the opaque black letters used in the signs, an increase in background luminance should not only provide more light but also increase the contrast between the characters and the background. In the presence of smoke, however, the background light tends to be scattered throughout the chamber. This causes the ambient level to be raised once the smoke density falls below the value that blocks the visible light. This scattering also causes some of the light to be reflected back on the surface of the sign, reducing the effective contrast ratio. The loss of sign effectiveness in the presence of smoke, therefore, is not only a function of light attenuation, but also a degradation of coherence or definition of the transmitted light and a greater reduction in contrast ratio than would be the case for a comparable change in background luminance level viewed under normal conditions.

The use of a luminous margin of fixed dimensions with all seven sign sizes may have influenced the results attributed to the background luminance level. With this design feature the signs with the smaller characters had a larger ratio of luminous surface area to the area covered by the characters than the signs with the larger characters, while the signs with the larger characters had more total luminous surface area. It remains to be determined if total luminous flux, arrived at by an optimal ratio of surface area and luminous intensity, may be more effective than luminous intensity alone as an independent variable of legibility of smoke obscured signs.

The optical properties of smoke are not the only factors that can affect vision. Smoke is often accompanied by oxygen depletion and increased carbon monoxide concentrations, which can impair not only the visual process but also the judgmental functions and physical responses required for escape (2). Depending on the composition of the combustion material, smoke may also contain varying concentrations of highly toxic substances which, even at sublethal levels, may cause severe irritation when dissolved in the moisture secreted by the eyes' mucous membranes and lachrymal glands, thus further reducing visual efficiency (2,3,5). The toxicity of the smoke does not necessarily correlate with its optical density and may therefore be quite high at relatively low optical densities.

A comparison of the mean optical densities of black and white smoke at the 89-cd/m^2 (26-fL) luminance level indicates they are approximately equal in their ability to mask the larger signs, but the black smoke obscures the smaller sign sizes at lower optical densities

(See Figure 4). The steeper slope of the curve for black smoke suggests that sign size (character height and luminous surface area) is more critical for readability in the presence of black smoke than with white smoke.

At two standard deviations below the means, black smoke appears considerably more effective than white smoke in obscuring all seven sign sizes. However, these more pronounced differences result from the greater variability of the black smoke data, with the standard deviations being approximately twice the magnitude of those for the white smoke data. This greater variability is not necessarily solely attributable to a specific optical quality of the black smoke itself but may also be due in part to uncontrollable variations in the characteristics of the black smoke produced on successive trials.

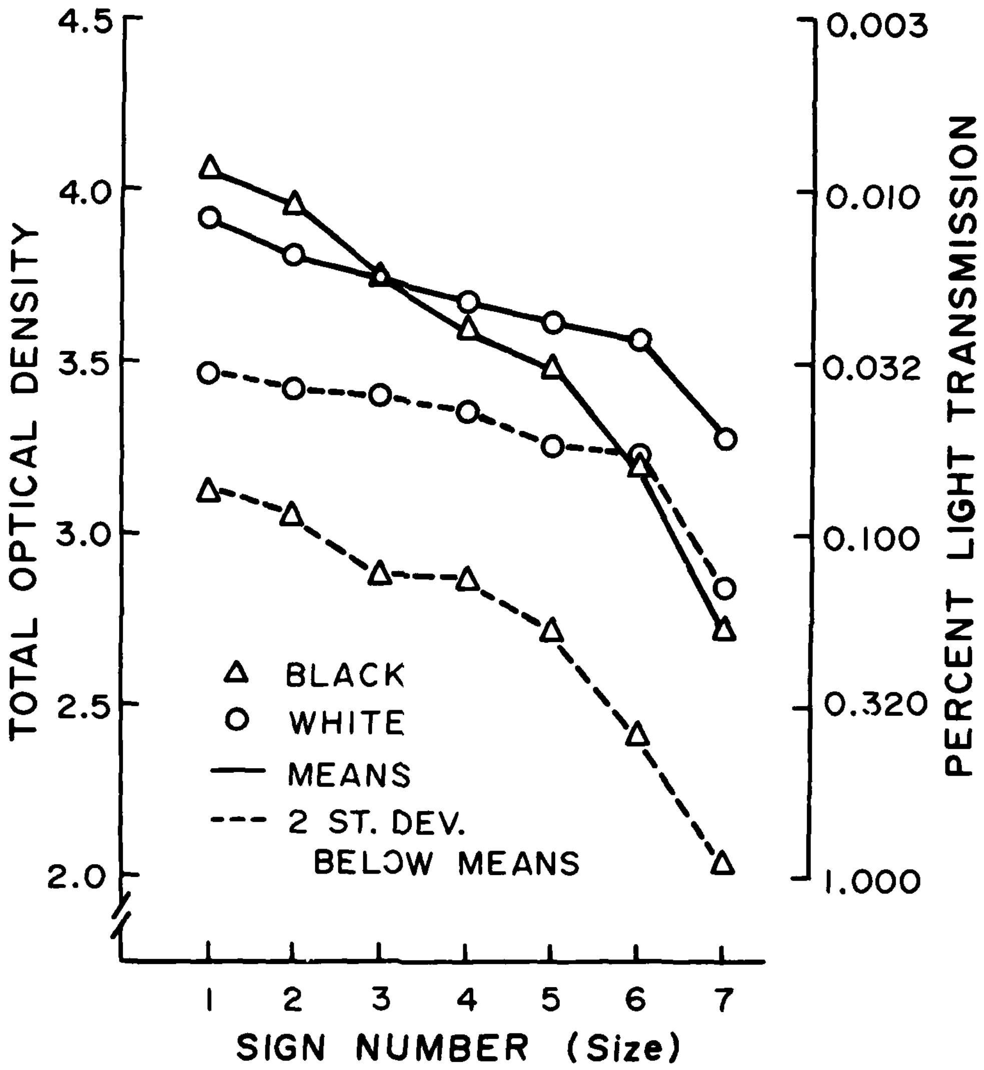

Figure 4. Comparison of black and white smoke densities at which seven sign sizes were identified when presented with a background luminance value of 89 cd/m^2.

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